JOURNAL
OF THE
WASHINGTON ACADEMY OF SCIENCES
VOL. VII SEPTEMBER 19, 1917 No. 15

PHYSICS.—*A two-stage mercury vapor pump.* H. F. STIMSON, Bureau of Standards. (Communicated by E. Buckingham.)

A "Condensation Pump" was described by Dr. Irving Langmuir[1] which not only produced the highest vacuum yet obtained with a pump but had a speed of exhaustion (cm.^{3}/sec.) greater than any previously existing high vacuum pump. The pump is exceedingly simple. A stream of mercury vapor from a boiler is sent down from a mouth or nozzle into a water jacketed chamber, entrains the gas coming past the nozzle, and condenses when striking the walls of the chamber, thus preventing flow of mercury vapor back to oppose the oncoming gas. This pump requires for its operation a primary vacuum of a few tenths of a millimeter of mercury pressure.

Conditions sometimes make it necessary or desirable to use as a source of primary vacuum either a water aspirator or some mechanical pump which fails to reach a pressure low enough to accommodate a single stage condensation pump. Two pumps modified by Prof. C. A. Kraus of Clark University to essentially the same form as Dr. Langmuir's later design were seen by the author early in September, 1916, working in series against a primary vacuum of 2 cm. given by a water aspirator. The expediency of using a water aspirator even at times when the vapor pressure of water is high has led to the present further development of the mercury vapor pump.

[1] Jour. Franklin Inst., **182**: 719. 1916; Gen. Elec. Rev., **19**: 1060. 1916.

This problem is different from Langmuir's in requiring in the mercury vapor pump the maintenance of a much larger pressure difference by means of a continuous supply of momentum in a manner analogous to the maintenance of a kite in air by the employment of the momentum of the wind. To sustain this large pressure difference a second stage is desirable, for could such a pressure difference be sustained and high vacuum attained with one stage, either a very large current of vapor would be required or the pump would have to be made so small that its speed would be very low. A second stage, on the contrary, in order to pump all the gas discharged from a pump working on high vacuum, need have only a hundredth the speed of the high vacuum stage or even less.

From dimensional reasoning it follows that whatever supports the pressure must have the same physical dimensions. Pressure has the dimensions of force per unit area and force has the dimensions of mass times velocity divided by time:

$$p = f/l^2 = mv/tl^2.$$

In order to make p large, l^2, the cross sectional area across which the stream of mercury vapor acts, can be made small. It is well known that a gas will flow through an orifice with a limiting velocity, which is the velocity of sound, if the ratio of final to initial pressure of the gas on the two sides of the orifice is less than a certain limiting fraction. This fraction for mercury vapor is about 0.49 and the velocity of sound referred to is that velocity determined by the temperature of the vapor in the orifice where it is adiabatically expanded to this limiting pressure. It appears then that mercury vapor can be expelled through an orifice with the velocity of sound by a boiler pressure a little more than twice the pressure of the supporting vacuum. When the boiler pressure is sufficient the velocity may be increased beyond the velocity of sound, as is done in the steam turbine, by an expanding nozzle, but such an enlargement requires an increased working cross section over which the pressure must be supported, thus limiting the advantage of the increased velocity. The term m/t can be increased by increasing the boiler pressure.

thus increasing the density of the discharged vapor. This dimensional reasoning will enable one to proportion properly the dimensions of the elements of a second or intermediate stage which will support a relatively large pressure.

If both stages are to be operated from the same boiler, as is extremely desirable, some change has to be made in the design of the high vacuum unit. On account of the increased boiler pressure a constriction will be necessary to cut down the flow of mercury vapor to a sufficiently low value. This can be most effectively accomplished by using a long DeLaval nozzle which will simultaneously introduce the advantages of reduction of pressure and increase of velocity.

These principles have been considered in the construction of pumps indicated in figure 1. Sample dimensions will be given to indicate working sizes, although the size will in most cases depend on the speed desired. The pump in question, including its boiler, was constructed entirely of Pyrex glass which is well adapted to this use and can be rapidly manipulated. The boiler was made of a half liter Erlenmeyer flask with slightly rounded bottom.

In the intermediate stage is a short slightly expanding nozzle

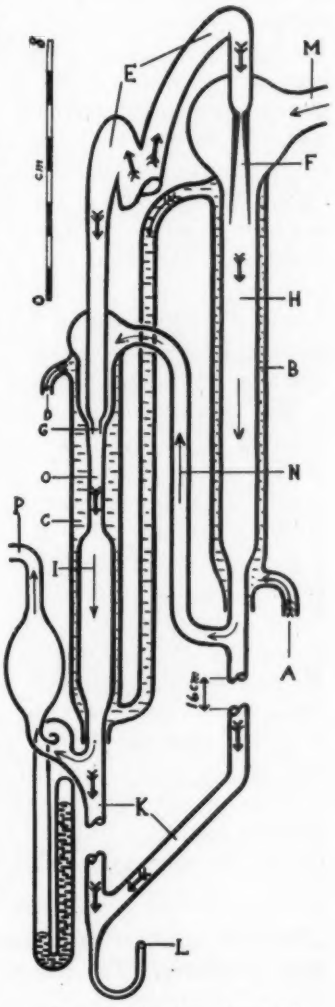

Fig. 1. Two-stage pump.

G, 3 mm. long with a throat 1.8 mm. in diameter, which sends the mercury vapor through a tube O, 3.5 mm. diameter, across which is supported the pressure from a water aspirator used as a fore pump. Care must be taken to leave sufficient clearance around the end of the nozzle G, and the tube O has been slightly tapered leaving a clearance of 0.7 mm., which seems to be sufficient to prevent condensed mercury vapor from collecting to make a seal. It appears that the size of this unit cannot be reduced below a certain limit determined by the surface tension of mercury. The pressure of the vapor in the boiler and feed tubes, E, has been raised to as high as 20 to 25 cm. of mercury, as is indicated while the pump is in action by the height of the mercury columns in tubes K. In the high vacuum stage a DeLaval nozzle, F, with a throat 0.7 mm. in diameter has been used expanding by about a ten to one taper to a diameter of 5 mm. discharging into a tube nearly a centimeter in diameter.

The operation of the pump is as follows. Cooling water entering at tube A flows up through the water jacket B above the lower end of nozzle F, up through the water jacket C above nozzle G, and out tube D. Mercury vapor from the boiler entering through tubes E flows through the nozzles F and G, is liquefied in the condensation chambers H and I, falls into the tubes K, and returns to the boiler through tube L. Gas from a vessel to be exhausted enters at M, flows past nozzle F, is compressed by the jet of mercury vapor in the condensation chamber H, and flows up through tube N to the intermediate pump. From here it flows past the nozzle G and is compressed through O in the chamber I to a pressure measured by the attached manometer, then out by tube P to the water aspirator.

Tests of the pump described above indicate a speed, when working against a primary pressure of 4 cm., of about 250 cm.^{3} per sec. when speed is defined[2] as

$$S = V/t \log p_1/p_2$$

where S is speed, V is volume, t is time, p_1 and p_2 are initial and final pressures. The pump gives a limit of pressure of non-

[2] GAEDE. Ann. d. Physik, (5) **41**: 365. 1913.

condensable gases very much less than a ten-thousandth of a millimeter of mercury as was shown on a MacLeod gage, which was the only low pressure measuring device available.

On account of questions that have been raised from time to time, which threw doubt on the assumption that the vapor flows through the intermediate pump with a velocity comparable with the velocity of sound, verificative experiments were made. A temporary rubber connection with pinch cock on the lower end of the tube K below the intermediate pump allowed the liquefied mercury to be caught and measured, thus giving the term m/t in the dimensional equation. The pressure difference supported by the pump was observed in the manometer arms K and the cross-section of the tube O is known. Computations of velocity from the dimensional equation give a value within a few per cent of the best available value for the velocity of sound under these conditions. The vapor density in the boiler is an independent datum and furnishes another means of computation, whose result indicates more conclusively that the assumptions of flow are verified as nearly as could be expected from the present incomplete knowledge of the properties of mercury vapor.

Some of the advantages of a pump of this design are apparent, namely, that it has a single boiler run by a single gas burner, a single line of cooling water, and is effectively a single unit with a direct air tight connection between the high vacuum stages. It is also noted that several paths conveniently open for free exhaustion with a fore pump are closed as soon as the mercury vapor pump is started. The advantage of not requiring a primary pressure less than 4 cm. is also apparent.

This type of pump could be employed in nearly all places where high vacuum is necessary. If mercury is objectionable either on account of its vapor pressure or its being an undesirable element in the region to be evacuated, the apparatus can be protected by a liquid air trap or possibly a gold foil trap. The speed of the pump when working on high vacuum can be increased by increasing the dimensions of the high vacuum unit. However, high speed, as has often been pointed out, is sometimes illusive, for a connecting tube 1 cm. in diameter and 0.5 meter long is

sufficient to cut the effective speed, of even as small a pump as the one described above, down to half, while a pump capable of infinite speed working through such a connection could only do as well as could the pump described above without such connecting tube.

When the time of initially reaching a sufficiently low pressure for the high vacuum pump to be effective becomes of importance the fore pumps can be made faster; however, this element is not often of so much consequence, for even a small water aspirator, working properly, in conjunction with the intermediate pump, will, in about five minutes, pump a volume of one liter down to a pressure sufficiently low for the high vacuum pump to begin effective operation and will pump larger volumes in proportionately longer times.

PHYSICS.—*Probe-wire measurements of anode fall of potential.* JOHN T. TATE and PAUL D. FOOTE, Bureau of Standards.

In connection with some work which the writers have in progress it was necessary to observe the amount of energy dissipated at the anode in a Wehnelt discharge tube. For this purpose a probe wire, or sound, was inserted in the anode glow and measurements were made upon the current flowing and upon the potential drop between the anode and sound.

In discharge tubes of this type it is easily possible to secure currents of several amperes with an anode fall of twenty volts or less. If the probe-wire circuit may be considered as obeying the ordinary laws of metallic circuits, it might at first appear that the resistance between the probe and the anode is small enough to permit accurate potential measurements by use of a high-resistance voltmeter instead of an electrometer. It was found, however, that the voltmeter readings were quite different from the electrometer readings.

Two explanations of this fact may be offered. That the probe wire on open circuit actually takes up the potential of the space surrounding it has been fairly well established.[1] On closed circuit the probe either takes up the potential of the

[1] SKINNER. Phys. Rev., 9: 97. 1917.

surrounding space or it does not. If we first assume that the probe wire, with a small current flowing through it, does acquire the potential of the surrounding space, or anode glow, then the power supplied to the anode by the main discharge current may be obtained by using the voltmeter reading. The voltmeter

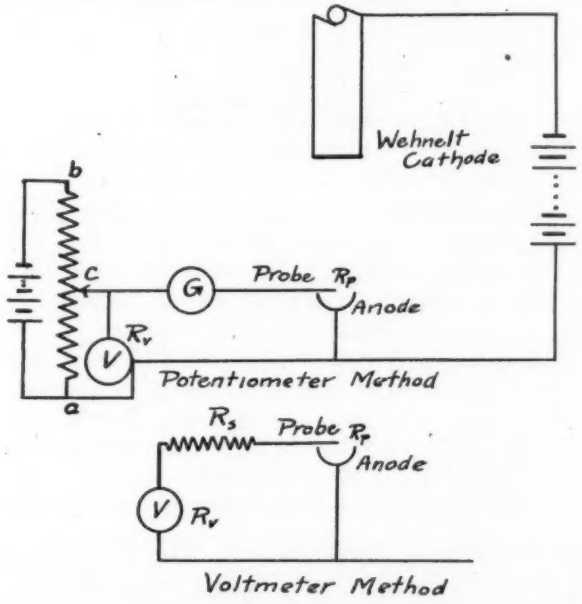

Fig. 1. Diagram of connections

readings are much smaller than the electrometer readings. Hence on the above assumption less power is developed at the anode while the voltmeter is connected. Since the potentials of the anode and cathode are fixed in the present experiment, the potential of the probe wire and anode glow must rise during the time the voltmeter is connected. The potential difference between the probe and cathode increases and, the main discharge current remaining constant, the difference in power developed at the anode in the two cases of electrometer and

voltmeter measurements must appear somewhere between the probe and the cathode.

The second assumption which may be made, and which the writers believe they have proved to be the correct explanation, is that the probe wire carrying a current does not take up the

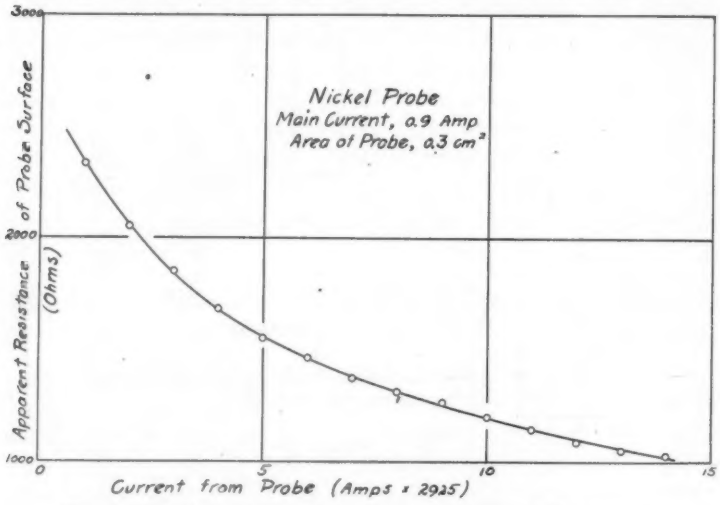

Fig. 2. Relation between the surface resistance and the current

potential of the space surrounding it. This would be the case if the probe were surrounded by a high-resistance film. Such films are known to exist[2] at the cathode, but the writers are not aware of measurements showing the presence of films at the anode. Any surface resistance of the probe must be due to its functioning as a secondary anode since the probe acts as a cathode through a metallic circuit alone.

In order to show the existence of a surface film at the probe, the apparatus was arranged as illustrated by figure 1.

The true anode drop was measured by using a potentiometric method, suggested by Dr. Swann, by adjusting the slide wire c for zero current in the galvanometer G and observing the read-

[2] SKINNER. Loc. cit.

ing of the voltmeter V. In the voltmeter method the relation was obtained between the variable resistance R_s and the voltmeter reading. If a film of resistance R_p exists at the probe the relation between the observed voltmeter reading V' and the voltage drop on open circuit, V, is as follows:

$$V = V' \frac{R_v + R_r + R_p}{R_v}$$

From this equation R_p, the film resistance, is readily obtained.

The values observed are plotted in figure 2. It appears that the film resistance decreases with increasing current through the probe for the range of currents used. Since the probe acts as an anode during voltmeter readings evidence has been obtained for the existence of an anode polarization similar to the polarization at the cathode in a highly ionized gas, as observed by Skinner. The present experiment would not distinguish between a true polarization and a secondary anode fall at the probe. This latter might be developed by the voltmeter current and, although the current is very small, might amount to several volts since, as is well known, the ordinary anode fall is pronounced even for minute currents. However, as Skinner has remarked, it is scarcely conceivable that a potential gradient could exist in a highly ionized space. The conditions relating to the true anode and the secondary anode, or probe, are not similar, since the ionization in the space surrounding the probe must be due almost entirely to the main current.

The proof that the first explanation of the difference in voltmeter and electrometer or potentiometer readings can not be correct may be had in the following experiment.

The temperature of the anode is a measure of the power expended in it. The anode was made in the form of a crucible and filled with tin—a very nonvolatile metal. The temperature of the molten tin was measured by a minute rare-metal thermocouple. A series of measurements showed that the temperature of the anode (and hence the power dissipated there) remained the same whether the voltmeter or potentiometer was connected to the probe, although the power measurements by

the voltmeter were 20 per cent less than those by the potentiometer. If the voltmeter readings were a correct indication of the potential of the probe, it would require that 20 per cent of the total energy be expended between the probe and cathode and radiated back to the crucible. Even if we make the most favorable assumption that all of this energy is expended at the probe, since the crucible subtends a solid angle of 2π at the probe while the radiation from the probe must take place through 4π, it is evident that only half of this energy, or 10 per cent of the total energy, could reach the anode, still leaving 10 per cent to be accounted for. This amount of energy was several times greater than possible errors of observation. Furthermore, the bright tin surface possesses such a high reflection coefficient that undoubtedly very little energy could be absorbed were it present in the form of radiation. Still further, one would have to explain how a probe carrying a thousandth or less of the main current could produce a potential fall for the entire current in a space already completely ionized.

Conclusion. A film of high resistance forms at the surface of a probe placed in the anode glow. If a voltmeter is employed for the measurement of anode fall, the readings must be corrected to allow for the potential drop through this high-resistance film. Such a correction would be impracticable on account of the varying nature of the film.

Since the probe functions as an anode during voltmeter readings, evidence has been obtained for the existence of an anode polarization similar to the polarization at the cathode in a highly ionized gas, as observed by Skinner. The magnitude of the anode polarization is very much less than the cathode polarization. This explains the fact observed by Skinner that in an auxiliary transverse discharge through the cathode glow the resistance and the current potential curves are characteristic of the auxiliary *cathode* employed.

RADIOTELEGRAPHY.—*Notes on the audion.* L. W. AUSTIN, U. S. Naval Radiotelegraphic Laboratory.

A number of observations on the deForest Hudson filament audion have been made at the U. S. Naval Radiotelegraphic Laboratory, which may be of general interest.

The gas pressure used in audion detectors is generally below 0.001 mm. of mercury. By substituting nitrogen for air, to prevent the burning out of the filament, it has been found possible to construct detectors at all pressures up to that of the atmosphere. The action at 3 mm. is entirely normal. Local oscillations are easily produced and the sensitiveness is fully as great, both for continuous and damped signals, as at the usual pressure. At 10 mm. the sensitiveness is about normal, but local oscillations are more difficult to produce. In the neighborhood of atmospheric pressure no local oscillations have been observed, and the sensitiveness to spark signals is much less than at the low pressures. The conditions in this case would undoubtedly be much improved by bringing the electrodes closer together. Even with the ordinary arrangement of electrodes, the changes in the grid and plate currents due to the incoming waves are similar to those observed in the usual vacuum. With 200 volts, the plate current amounts to 20 or 30 microamperes.

Another series of observations has been made on the effect of the direct current voltage between the grid and filament on grid and plate signals. By grid and plate signals are meant the changes in grid and plate current brought about by an impressed alternating e.m.f. In the case of radio frequency signals a tuned closed circuit is connected in the usual way to the filament and through a stopping condenser to the grid. In this case the stopping condenser is shunted by a circuit containing a potentiometer for varying the D. C. grid potential and a galvanometer for measuring the grid current. In the case of low frequency excitation no tuned circuit is used but the filament is connected to the grid through the direct current potentiometer already mentioned, the galvanometer, and a slide wire alternating current potentiometer from which the required alternating voltage

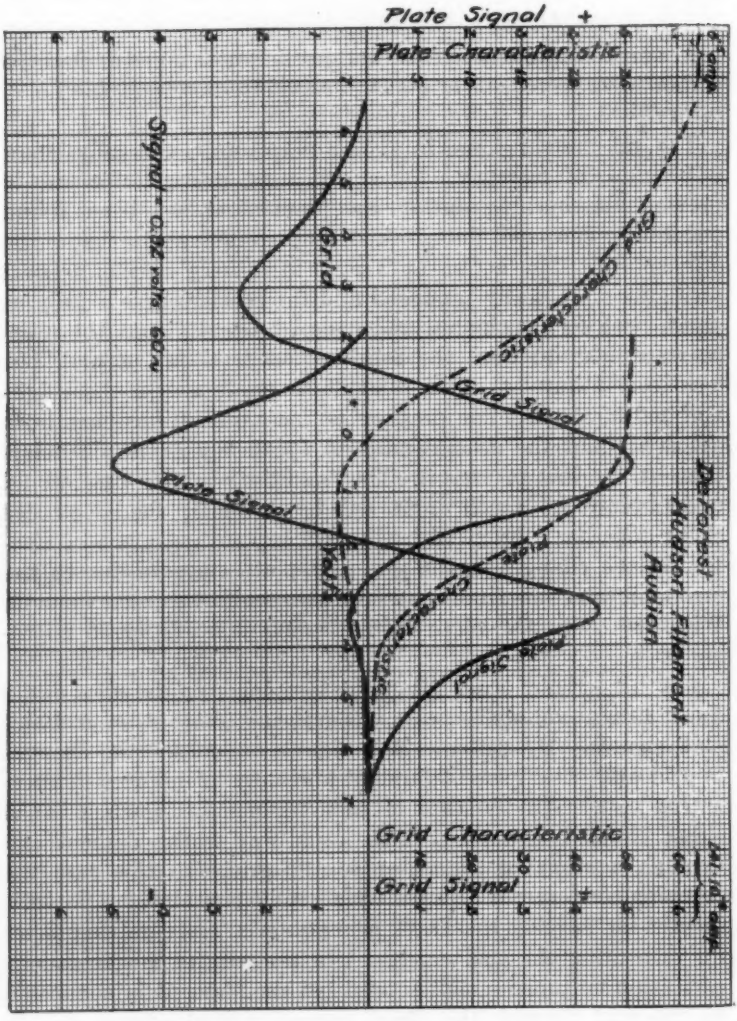
Plate Signal +
Plate Characteristic
Grid Characteristic
Grid Signal
Plate Signal
Grid Signal
Grid Characteristic
Plate Characteristic
Plate Signal
Grid Signal
Grid Characteristic
Plate Characteristic
De Forest
Audion
Filament

Fig. 1

is applied to the circuit. In both cases the plate circuit contains the usual dry cell battery of about 25 volts, the telephones, and a galvanometer for the measurement of the plate current. In the observations shown in figure 1 the gas pressure is that usually found in bulbs of this type.

The figure shows the grid and plate characteristics and also the grid and plate signals as defined above. The alternating e.m.f. in this case was 0.92 volt, with a frequency of 60 cycles. In the neighborhood of zero D. C. grid voltage the usual decrease of plate current and increase of grid current are noted, while with changing grid voltage the signals change both in magnitude and sign. These changes are apparently to be explained by the changes in curvature of the two characteristics.

The same curves are obtained if undamped radio frequency excitation of the same strength is used in place of the 60 cycles. In this case the grid galvanometer is shunted with a low non-inductive resistance to allow the oscillations to pass freely. Here the stopping condenser plays little part. If, however, a megohm is placed in series with the grid galvanometer so as to force the oscillations through the stopping condenser, the appearance of the curves is much changed. The grid signal is positive and nearly uniform over a wide range of grid D. C. voltage, while the plate signal is similarly negative except for strongly negative grid where both signals reverse slightly. Apparently here some other effects appear in addition to those due to the changes in grid and plate characteristics.

This work is still in progress and will be described later at greater length.

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